MEASUREMENT OF RESIDUAL AND THERMALLY-INDUCED STRESS IN A RAIL

This invention relates to a method and apparatus for determining residual stress in a ferromagnetic object such as a rail of a railway line, preferably using an electromagnetic probe.

The stresses in structures such as rails, bridges and pipelines, complex mechanisms such as vehicles and machinery, or simple devices such as struts, cables or bearings arise from various causes including changes of temperature, and the loads and pressures due to use. There may also be residual stresses arising from the fabrication of the structure or device, and any bending that the structure or device was subjected to during construction; the residual stresses arising from fabrication will also be affected by any stress-relieving heat treatment. A way of measuring stress in a steel plate is described in US 5 828 211 (GB 2 278 450), this method using a probe containing an electromagnetic core to generate an alternating magnetic field in the plate, and then combining measurements from two sensors, one being a measure of stress-induced magnetic anisotropy (SMA), and the other being a measure of directional effective permeability (DEP). The probe is gradually turned around so the magnetic field has a plurality of different orientations in the plate, and these measurements are taken at each such orientation. The probe enables the stress to be measured near the surface, the depth of penetration depending upon the frequency.

In the case of railway lines, thermally-induced stresses are a contributing factor for both rail breaks (when the rail temperature falls, for example in winter), and for rail buckling (when the rail temperature rises, for example in summer). Traditionally in continuous-

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welded rail these problems are minimised by initially
installing the rail in a state of tension, such that the
thermal stresses would become zero if the rail
temperature were to rise to a "stress-free temperature"
5   which is selected such that in practice the thermal
stresses do not reach excessive values. It would be
desirable to be able to monitor the thermally-induced
stresses in a rail, but this is no simple matter. As a
rule, stress measurement techniques measure the total
10 stress, which is the sum of the thermally-induced stress
and the residual stress (as tensors); to determine the
thermal stress it is therefore necessary to also
ascertain the residual stress. This can be measured by
measurements on a rail that is unconstrained, for example
15 by cutting out a section of rail, but a nondestructive
measurement technique would be desirable. (In this
specification the term thermal stress or thermally-
induced stress refers to the difference between the total
stress and the residual stress.)
20

    It will also be appreciated that accurate
measurement of rail temperature is also very difficult to
achieve, because of varying environmental conditions
along a length of rail and because of the comparatively
25 poor thermal conductivity of rail steel; an uncertainty
in the mean temperature of any less than about +/- 2°C
would be difficult to achieve. Temperature measurements
in sunshine are likely to be even harder.

30   According to the present invention there is provided
a method for determining the residual stress and the
thermally-induced stress in a rail, the method comprising
measuring the stresses in part of the rail remote from
the railhead in a direction perpendicular to the
35 longitudinal axis of the rail, and in a direction
parallel to the longitudinal axis, determining from the

stress in the perpendicular direction an estimate of the
residual stress in the parallel direction, and hence by
comparing the measured stress in the parallel direction
to the estimated residual stress in the parallel
5   direction determining the thermally-induced stress.

It has been discovered that residual stresses in
rails vary from rail to rail, and through the life of a
rail. However the lifetime variation can be minimised by
10 considering stresses in regions remote from the railhead,
that is to say in the web or possibly the foot of the
rail. The residual stresses in both the parallel and
perpendicular directions are principally caused by the
straightening which is the final stage of manufacture of
15 the rail, and consequently can be related to each other.
In the web, for example, the residual stresses are
typically compressive, in the region 120 to 220 MPa in
the parallel direction, and 50 to 100 MPa in the
perpendicular (vertical) direction. It should be
20 appreciated that the variations in thermally-induced
stress in the parallel direction in a straight track are
only about 2.4 MPa/°C, so that variations in the residual
longitudinal stress arising from the manufacturing
process of say 50 MPa are generally much larger than the
25 thermally-induced stresses.

In one embodiment of the invention the stress in the
perpendicular direction is correlated with the residual
stress in the parallel direction; in an alternative
30 embodiment, the stress in the perpendicular direction is
measured at different depths, and its variation with
depth is correlated with the residual stress in the
parallel direction. This alternative approach does not
require absolute measurements of stress in the vertical
35 direction, but only the difference in stress for
different depths, and this may be desirable.

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Preferably the stress is measured using an
electromagnetic probe. In the preferred stress-
measurement method the probe comprises an electromagnet
5 means, means to generate an alternating magnetic field in
the electromagnet means and consequently in the rail, and
a magnetic sensor arranged to sense a magnetic field due
to the electromagnet means; and the method comprises
resolving signals from the magnetic sensor into an in-
10 phase component and a quadrature component; mapping the
in-phase and quadrature components directly into stress
and lift-off components; and deducing the stress from the
stress component so determined.

15 The mapping requires a preliminary calibration, with
a specimen of the material, to determine how the in-phase
and quadrature components of the signal vary with lift-
off (at a constant stress) and vary with stress (at a
constant lift-off), and deducing from the calibration
20 measurements the applicable mapping for any stress and
any lift-off. The mapping may be represented in the
impedance plane (i.e. on a graph of quadrature component
against in-phase component) as two sets of contours
representing signal variation with lift-off (for
25 different values of stress) and signal variation with
stress (for different values of lift-off), the contours
of both sets being curved. The contours of one set
intersect the contours of the other set at non-orthogonal
angles. Surprisingly it has been found that the angles at
30 which the constant lift-off contours intersect any one
contour of constant stress are all the same. Hence
measurements taken along a few contours of each set
enable the positions of the other contours of each set to
be determined. This method of interpreting the signals
35 and distinguishing between stress and lift-off is
described in detail in WO 03/034054.

Surprisingly this simple mapping has been found to
give an accurate representation of the variation of the
signals with material property (e.g. stress), and
5   provides a simple way to distinguish these variations
from variations arising from lift-off or other
geometrical variations such as surface texture or
curvature.

10   Preferably the electromagnet means comprises an
electromagnetic core and two spaced apart electromagnetic
poles, and the magnetic sensor is preferably arranged to
sense the reluctance (or flux-linkage) of that part of
the magnetic circuit between the poles of the
15   electromagnet means. It is also desirable to arrange for
such measurements to be taken with a plurality of
different orientations of the magnetic field, at a single
location on the object. This may be achieved using a
single probe that is rotated at that location,
20   measurements being taken with different orientations of
the probe. The sensor provides a measure of the
permeability of the material through which the flux
passes between the poles; the corresponding measurements
at different probe orientations at a location on the
25   object hence indicate the effective permeability in
different directions.

The probe may also include a second magnetic sensor
between the two poles and arranged to sense magnetic flux
30   density perpendicular to the direction of the free space
magnetic field between the poles. This second sensor
would detect no signal if the material were exactly
isotropic; however stress induces anisotropy into the
magnetic properties of the material, and so the signals
35   received by the second sensor (or flux-rotation sensor)
are a measure of this stress-induced magnetic anisotropy.

The variations in the flux rotation signals at different probe orientations, at a location on the object, enable the directions of the principal stress axes to be accurately determined. The flux rotation signals can

5   also be related to the stress.

The probe may also include a third magnetic sensor (a flux-leakage sensor) between the poles arranged to sense magnetic flux density parallel to the free space

10 magnetic field. This third sensor detects flux leakage which is influenced by changes in material properties, lift-off, and cracks. As with the flux-linkage sensor, measurements at a location are preferably made at different probe orientations.

15

The reluctance (or flux-linkage) signal from the probe is preferably backed-off, i.e. processed by first subtracting a signal equal to the signal from that sensor with the probe adjacent to a stress-free location. The

20 backed-off signal is then amplified so the small changes due to stress are easier to detect. This backing off is performed after resolving into in-phase and quadrature components but before correcting for lift-off, for example by the mapping described above. Preferably the

25 signals from the probe are digitized initially, and the backing-off and the lift-off correction are performed by analysis of the digital signals.

Generally, the more different probe orientations are

30 used for taking measurements the more accurate the determination of stress levels can be. The measurements at different probe orientations at a particular location would usually be obtained by rotating the probe, but alternatively might be obtained using an array of probes

35 of different orientations that are successively moved to that location. It will be appreciated that measurements

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of stress at different depths below the surface, where
this is required, may be achieved by generating the
alternating magnetic field with different frequencies.

5   The invention will now be further and more
particularly described, by way of example only, and with
reference to the accompanying drawings, in which:

        Figure 1 shows a diagrammatic view of an apparatus
10 for measuring stress;

        Figure 2 shows a longitudinal sectional view of a
probe for use in the apparatus of figure 1;

15   Figure 3 shows graphically the variation of the
backed-off quadrature and in-phase components of flux
linkage with variations of lift-off, and with variations
of stress; and

20   Figure 4 shows graphically the correlation between
the signals representing stress in the vertical and
longitudinal directions in rail webs.

        Referring to figure 1, a stress measuring apparatus
25 10 includes a sensor probe 12 comprising sensors for
flux-linkage, flux-rotation and flux-leakage, the probe
12 being attached to an electric motor 14 which can be
held by an operator, so the motor 14 can turn the probe
12 with one end adjacent to a surface of a steel object
30 16 (the web of a rail in this case) in which the stresses
are to be determined. The sensor probe 12 and motor 14
are connected by a 2 m long umbilical cable 17 to a
signal conditioning/probe driver unit 18. The unit 18 is
connected by a long umbilical cable 19 (which may for
35 example be up to 300 m long) to an interface unit within
a microcomputer 20, which has a keyboard 21. Operation

of the apparatus 10 is controlled by software in the
microcomputer 20.

Referring now to figure 2, the probe 12 is shown
5 detached from the motor 14, in longitudinal section
although with the internal components shown in elevation
(the connecting wires within the probe 12 are not shown).
The probe 12 comprises a cylindrical brass casing 24 of
external diameter 16.5 mm and of overall height 60 mm,
10 the upper half being of reduced diameter whereby the
probe 12 is attached to the motor 14. The upper half of
the casing 24 encloses a head amplifier 25. The lower
half encloses a U-core 26 of laminated mu-metal (a high
permeability nickel/iron/copper alloy) whose poles 28 are
15 separated by a gap 7.5 mm wide, and are each of width 2.5
mm, and of thickness 10 mm (out of the plane of the
figure). The poles 28 are in the plane of the lower end
of the casing 24, which is open. Around the upper end of
the U-core 26 is a former on which are wound two
20 superimposed coils 30. One coil 30a (which has 200
turns) is supplied with the sinusoidal drive current from
the unit 18; the other coil 30b (which has 70 turns)
provides flux linkage signals.

25   Between the two poles 28 is a former on which is
wound a 1670-turn rectangular coil 32, about 4 mm high
and 6 mm wide, and 6 mm-square as seen from below, the
windings lying parallel to the plane of the figure so the
longitudinal axis of the coil 32 is perpendicular to the
30 line between the centres of the poles 28. The coil 32 is
supported by a support plate 34 fixed between the arms of
the U-core 26 so the lower face of the coil 32 is in the
plane of the poles 28. The coil 32 provides the flux-
rotation signals. If a flux-leakage signal is required,
35 a coil may be wound on the same former but with windings
perpendicular to the plane of the figure. All the

signals are amplified by the head amplifier 25 before
transmission to the unit 18.

In operation of the system 10, the motor 14 is
5   supported so the lower end of the probe 12 is adjacent to
the surface of a steel object and the longitudinal axis
of the probe 12 is normal to the surface. An alternating
current of the desired frequency and amplitude is
supplied to the drive coil 30a, so the magnetic field in
10 the object 16 oscillates about zero with an amplitude
much less than saturation. To set up the system 10,
measurements are first made using an object of the same
type of steel as the rail 16 but in which the stresses
are negligible. The in-phase and quadrature components of
15 the flux linkage signal (i.e. the component in phase with
the drive current, and the component differing in phase
by 90°) received by the microcomputer 20 are each backed
off to zero, and the backing off values are then fixed.
During all subsequent measurements the flux linkage
20 components are backed off by these same amounts (i.e.
subtracting a signal equal to the component observed at a
stress-free location).

Stress measurements can be taken by placing the
25 probe 12 adjacent to the web of the rail 16. The
orientation of the line joining the centres of the poles
28 (referred to as the orientation of the probe 12) is
noted relative to a fixed direction on the surface. The
motor 14 is then energized to rotate the probe 12, for
30 example in a step-wise fashion 10° at a time through a
total angle of 360°. At each orientation of the probe 12
all the signals are measured.

It will be appreciated that the procedure of the
35 invention is applicable with many different probes. The
probe 12 might for example be modified by using a U-core

26 of a different material such as silicon iron (which
can provide higher magnetic fields), or indeed the drive
coil might be air-cored. The probe might be of a
different shape or size; probes ranging in size between
5   about 3 mm and 75 mm have been used for different
purposes. In particular, for measurements on rails, a
probe of diameter in the range 20 mm to 40 mm, e.g. 30
mm, would be suitable.

10   The flux rotation signals vary sinusoidally with
probe orientation, so the orientation at which they have
their maxima and minima can be determined. The
directions midway between these two orientations are the
directions of the principal stress axes. Measurements of
15   flux rotation are therefore useful if the principal
stress directions are unknown. The values of flux linkage
and flux leakage also vary sinusoidally with probe
orientation (in antiphase with each other), and the
values are observed at the principal stress directions.
20   If the principal stress directions are already known,
then the probe 12 might instead be merely oriented to
those directions, and the measurements made; no rotation
of the probe 12 would be necessary.

25   The values of the stresses in the web in the
vertical (i.e. perpendicular to the longitudinal axis)
and longitudinal directions can be determined from the
experimental measurements of flux linkage with the probe
12 oriented in those directions. This requires
30   calibration of the apparatus 10, taking measurements on a
sample of material of the same type as that of the rail
16, while subjecting it to a variety of different
stresses. This may be done with a rectangular strip
sample in a test rig, flux linkage measurements being
35   made at the centre of the sample where the principal
stress direction is aligned with the axis of the test

rig. Referring to figure 3 this shows the backed-off
flux-linkage in-phase and quadrature components obtained
in such a test rig, the measurements being made with a
drive frequency of 70 Hz, and the specimen being a steel
5   bar. A first set of measurements were made at
progressively larger values of lift-off, L, but with no
stress, S. This gives the lift-off contour A, the lift-
off varying between 0 and 220 microns. Similar lift-off
contours A are obtained for other fixed values of stress,
10   those for S = 250 MPa tension and compression being
shown. Measurements were then made at a range of
different fixed values of lift-off, L, with varying
stresses, S (both compression and tension), providing the
contours B.
15

It will be appreciated that the contours A are
curved, and the contours B are not orthogonal to the
contours A, but that they intersect at substantially
constant angles along any one lift-off contour A.
20   Consequently it is only necessary to make calibration
measurements sufficient to plot a few such contours A and
B, and the shapes of the other contours can be predicted.

After calibrating the probe 12 in this manner,
25   measurements of stress can be readily made from
observations of flux linkage signals (resolved and backed
off), as the contours enable the changes due to lift-off
to be readily distinguished from changes due to stress.
Any particular position in the impedance plane (i.e. in
30   the graph of quadrature against in-phase components)
corresponds to a particular value of stress and a
particular value of lift-off. The mapping between (in-
phase, quadrature) coordinates and (stress, lift-off)
coordinates may be carried out graphically, referring to
35   such contours, or by calculation. For example if the
flux linkage signal has the in-phase and quadrature

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components of the position marked X, this corresponds to a lift-off of about 80 microns and a stress of about 125 MPa. Alternatively this value X may be translated (along the broken line Y) along a contour A of constant stress
5   to find the in-phase and quadrature components at position Z that would be obtained with zero lift-off.

The value of stress found in this way is, it will be appreciated, the uniaxial stress that would provide that
10 value of the flux linkage signal. If the stresses are actually biaxial, then a further calibration must be carried out with a cross-shaped sample in a test rig, flux linkage measurements being made at the centre of the sample where the principal stress directions are aligned
15 with the axes of the test rig. Hence a graph or map may be obtained for a range of values of stress on one axis (say the x-axis) and for a range of values of stress in the other axis (say the y-axis), with contours each of which shows the values of biaxial stress that give a
20 particular value of apparent uniaxial stress along the x-axis; and a similar graph may be obtained with contours showing values of biaxial stress that give a particular value of apparent uniaxial stress along the y-axis. Hence from measurements of apparent uniaxial stress along
25 the two principal stress axes obtained as described earlier, the biaxial stress can be determined.

It will again be appreciated that the biaxial stress may be determined either graphically or by calculation in
30 this way. Apparent values of uniaxial stress (in MPa) may be used for this purpose, or alternatively the numerical value of the flux linkage signal (in mV), either the in-phase or quadrature value, obtained by eliminating the effect of lift-off as described in
35 relation to figure 3, may be used. Although the above method of correcting for lift-off has been described in

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relation to flux-linkage signals it is equally applicable
to flux-leakage signals.

In the case of rail steels it has been found that
5   the signals, if corrected for lift-off (for example as
described above), both those for flux-linkage and those
for flux-leakage, can be related almost linearly to the
stress.   (It will be appreciated that the flux-leakage
signals increase as the flux-linkage signal decrease.)
10   Measurements have been taken on nine different rails of
different ages and from different manufacturers, on cut
sections so that there is no thermally-induced stress;
each section of rail was 3 m long or longer, and of the
same grade of steel (220 grade) and cross-section (BS
15   113A).   All the measurements were taken more than 0.3 m
from either end to avoid those regions in which the
residual stresses may have relaxed, and several different
measurements were taken on each rail, along its length.
There has been found to be a clear positive correlation
20   between the signals in the longitudinal and vertical
directions (i.e. parallel and perpendicular to the
longitudinal axis), and so between the residual stresses
in the longitudinal and vertical directions.

25   Referring now to figure 4, this shows graphically
the flux linkage signal in the vertical direction (L1)
and the flux linkage signal in the longitudinal direction
(L2), each signal having been corrected for lift-off, the
crosses showing the mean values for the measurements
30   taken along each one of the nine different rail
specimens, and the standard deviation of the
discrepancies from the straight line P; the scatter along
the straight line P is not indicated.   (The numerical
values on the axes are proportional to the signal
35   voltages, 10 on the scale corresponding to 23 mV.) The
positive correlation is clearly evident, and the straight

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line graph P may be represented by the equation:

L1 = 1.398 L2 + 30.04

5   This experimentally-observed relationship between the
     vertical and longitudinal flux-linkage signals
     corresponds to a linear relationship between the vertical
     and longitudinal residual stresses. By measuring the
     stress in the vertical direction in a rail that is in
10   situ (and in which there therefore may be thermally-
     induced stresses), this relationship enables the residual
     stress in the longitudinal direction to be determined.
     The difference between this and the observed total stress
     in the longitudinal direction consequently represents
15   what is referred to as the thermally-induced stress.

     The diamonds Q1, Q2 and the squares R1 and R2 on the
     graph show measurements made on a single rail in situ at
     different places along the rail after repeated cutting,
20   re-stressing, and welding. The diamond Q1 shows the
     measurements on the rail before cutting, and Q2 shows the
     measurements after the rail has been cut. In this cut
     condition the rail is free standing, and there should
     therefore be no thermally-induced stress. As expected,
25   Q2 lies very close to the straight line graph P. The
     square R1 shows the measurements at a different position
     on the same rail, after the rail has subsequently been
     restressed and welded, and R2 shows the measurements
     after the rail has again been cut. Once again, in the
30   cut condition, one would expect there to be no thermally-
     induced stress; this is confirmed by the proximity of R2
     to the straight line P.

     It will thus be appreciated that from measurements
35   such as Q1, the total longitudinal stress corresponds to
     the value L2 = -11.6; without cutting the rail you can

predict that the residual stress corresponds to the value L2 = -15.3 (ie the L2 value on the line P at the same value of L1). Consequently the thermally-induced stress corresponds to the difference between these two values.

5 The thermal stress can be expressed in terms of the stress-free temperature, for example by assuming that the longitudinal stress changes by 2.4 MPa/°C; the faint lines parallel to the line P each represents a difference of 10°C between the measurement temperature and the

10 stress free temperature. For example, Q1 corresponds to a stress free temperature about 15°C above the measurement temperature, while R1 corresponds to a stress free temperature about 20°C above the measurement temperature.

15

Measurements of the stress free temperature made in this way can be compared to those measured using a strain gauge and cutting the rail. In one case, for example, measurements of the stress free temperature determined as

20 described above gave results of 24°C and 31°C, while the stress free temperature determined using the strain gauge and rail cutting gave results of 26°C and 28°C.

The measurements taken above utilise flux linkage,

25 but alternatively flux leakage signals could have been used.

The above signals were taken at 70 Hz, but alternatively the measurements might be made at a

30 different frequency. In each case there will be a similar relationship between the vertical and longitudinal residual stresses. However, measurements at a higher frequency such as 500 Hz penetrate to a shallower depth into the rail, and this has been found to

35 give a steeper straight line P, because the vertical stresses are greater nearer the surface. Any instability

in the performance of the instrument tends to affect
measurements of vertical and longitudinal stress equally,
so the frequency is preferably selected to provide a
straight line P whose gradient is 1.0; such instabilities
5   would then move the measured point parallel to the line
·P, and so would not affect the accuracy of the
measurement of stress free temperature.

In a further alternative, the residual longitudinal
10   stresses may be correlated with the variation of vertical
stress with depth. From measurements taken at several
different frequencies, it is possible to deconvolve the
measurements by assuming a functional form for the
variation with depth (as described in US 2003/0071614A)
15   and obtain values for the vertical stress at different
depths. This can enable the exact variation of stress
with depth to be determined. More simply, measurements
might be taken at say two different frequencies, and the
difference between those measurements correlated with the
20   longitudinal stress measurements.

It will be appreciated that the present invention
enables the stress-free temperature to be determined in a
non-destructive fashion. It is applicable on both
25   straight and curved tracks; it does not require the rail
to be disconnected from the sleepers; and it is
applicable whether the rail is under tension or
compression.

30